Risk-Informed Approach to Penstock Safety

NW Hydro Users Group
September 25, 2012

Penstock Risk Assessment

- Failure Modes
- Consequences

FERC Database

- Geotechnical Issues (23)
- Deterioration (21)
- Vacuum (15)
- Flood (6)
- Water Hammer (5) 3 included some degree of operator error
- Fabrication Errors (4)
- Couplings (4)
- Ground Water/Operator Error (1 each)
- Other/Unknown (10)

Hazards by Regions

	Total	ARO	CRO	NYRO	PRO	SFRO
Unknown	2	0	0	2	0	0
Coupling	4	0	0	1	1	2
Deterioration	21	1	2	8	8	2
Fabrication	4	0	0	0	2	2
Flood	6	0	0	5	1	0
Geotechnical	23	3	0	2	8	10
Ground Water	1	1	0	0	0	0
Operation	1	0	0	1	0	0
Other	8	2	1	1	3	1
Vacuum	15	0	1	6	6	2
Water Hammer	5	0	0	0	1	4
Total	90	7	4	26	30	23

FERC Penstock Data

	ARO	CRO	NYRO	PRO	SFRO
Ave. Head	231	155	93	306	724
Max. Head	1380	854	1148	2387	2616
Min. Head	14	18	3	14	6
Ave. Diameter	12	10	10	8	5
Max. Diameter	26	49	30	28	25
Min. Diameter	2	2	<1	<1	<1
Ave. Length	478	846	519	2024	3698
Max. Length	6590	19000	18412	65472	42000
Min. Length	2	5	10	10	2

All data in feet

Geotechnical/Geological

- Soil/Rock movement including landslides
- Rockfall
- Bearing failure

Equipment Malfunction

- Vacuum
  - Air valve failure
  - Debris plugging air vents
  - Icing of air vents
  - Mis-operation
- Water Hammer
  - Governor failure / wear
  - Wicket gate failure
  - Pelton needle failure
  - Mis-operation


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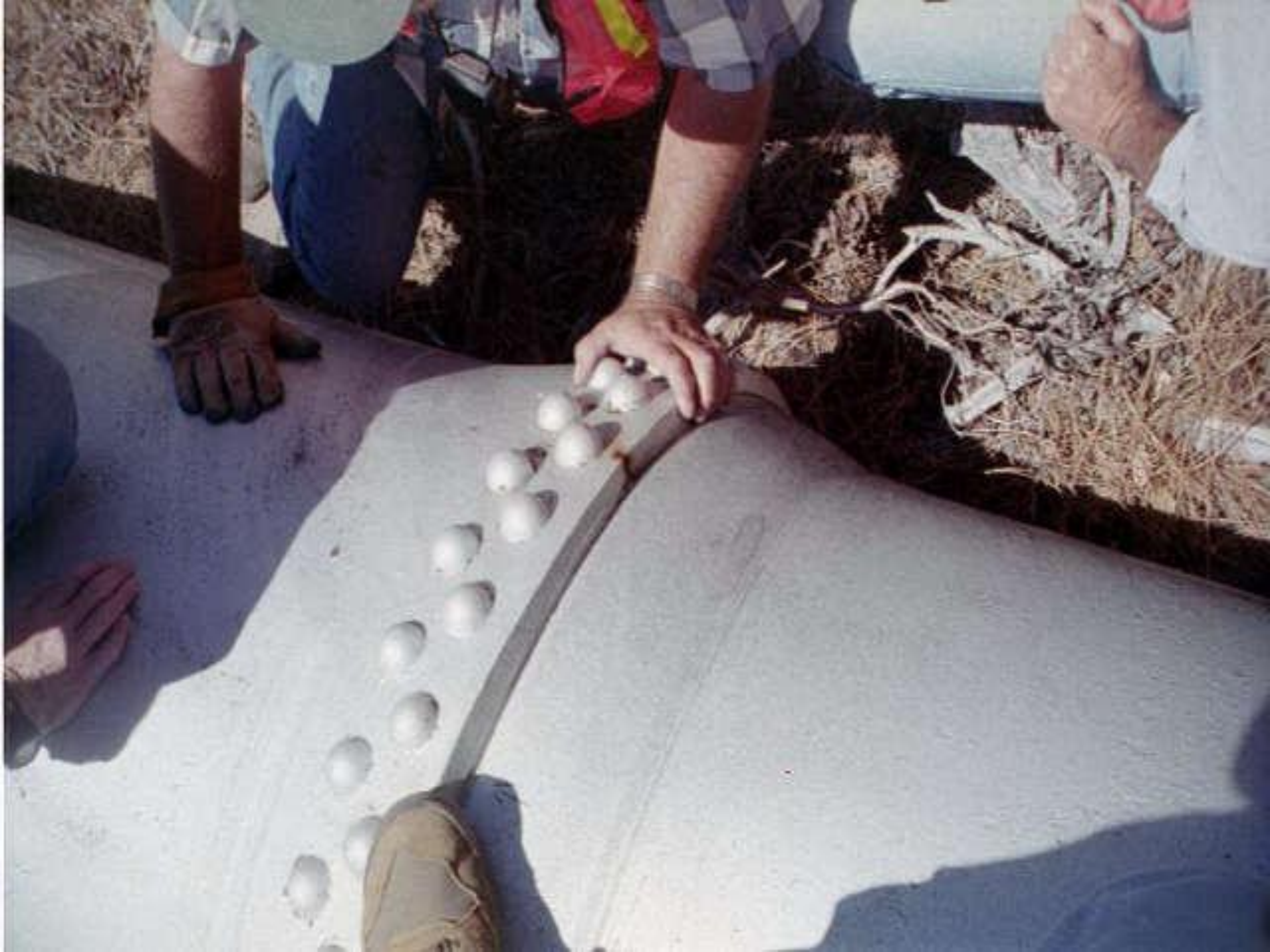
Aging/Deterioration

- Lack of Maintenance
- Erosion of invert
- Stress-Corrosion Cracking
- Cavitation
- Acidic Soil



A
Can #8
2 ¼”

Fabrication

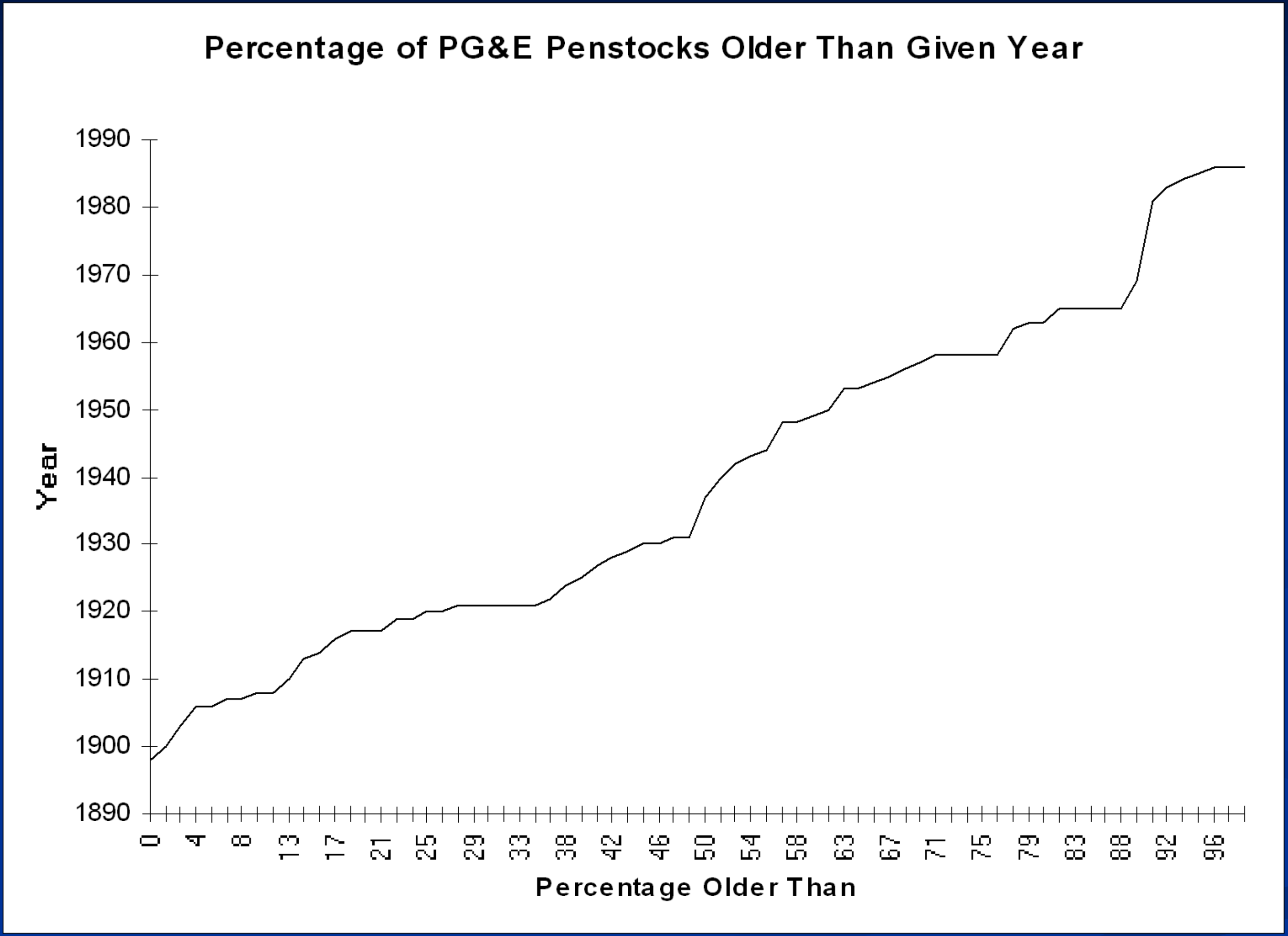
Flood

Organization/Operator Error

Consequences

- Reconstruction
  - Penstock
  - Powerhouse
  - Switchyard
- Lost Generation
- Property Damage
- Loss of Life
- Environmental Mitigation

Risk-Informed Approach to Penstock Safety



Percentage of PG&E Penstocks Older Than Given Year
Year
1990
1980
1970
1960
1950
1940
1930
1920
1910
1900
1890
0
4
8
13
17
21
25
29
33
38
42
46
50
54
58
63
67
71
75
79
83
88
92
96
Percentage Older Than

R&D Program

- Establishment of penstock database
- Development of risk assessment program

Penstock Database

- MS Access format
- Included information on:
  - Head
  - Flow
  - Material
  - Length
  - Thickness
  - Age
  - etc.

Risk Assessment Methodology

- Focuses on:
  - Hazards
  - Consequences
- Determines Risk

Definitions

- Hazard - Conditions that by themselves or in conjunction with other conditions can lead to a penstock failure - expressed in terms of occurrences/year
- Consequence - Damages that may occur in the event of a failure expressed in terms of $ (Life safety consequences were not considered)
- Risk - The product of Hazards and Consequences expressed in terms of $/year
- Probabilistic Risk Assessment
  - A range of possible values is estimated for the probability of occurrence for pertinent hazards and consequences
  - The program determines the probabilistic risk for each penstock

Hazards Considered

- Geotechnical
- Hydrologic
- Seismic
- Equipment Malfunction
- Site Specific

Consequences Considered

- Pipe replacement
- Geotechnical stabilization
- Damage to powerhouse
- Damage to switchyard/transmission facilities
- Lost generation
- Property damage
- Environmental damage

Cost Spreadsheet

	C1 - Pipe Replacement					C2 - Geotechnical				C3 - Powerhouse				
Name	Cmin	Cexp	Cmax	Std Dev.	Cstoch1	Cmin	Cexp	Cmax	Cstoch2	Pstrike	Cmin	Cexp	Cmax	Cstoch3
A1	908	2214	3820	221	2210	2500	5000	15000	5438	1.00	0	5000	10000	3675
A2	962	1202	1442	120	1194	2500	5000	15000	5323	1.00	0	500	1000	365
A3	561	962	1442	96	964	2500	5000	15000	5283	1.00	0	250	500	187

C4 - Switchyard/Transmission				C5 - Lost Generation				C6 - Property Damage			
Cmin	Cexp	Cmax	Cstoch4	Cmin	Cexp	Cmax	Cstoch5	Cmin	Cexp	Cmax	Cstoch6
2700	5400	16200	5739	1,219	2,439	7,316	2534	2000	4000	12000	4274
2700	5400	16200	5666	114	227	682	242	2000	4000	12000	4237
2700	5400	16200	5754	93	187	560	197	2000	4000	12000	4237

C7 - Environment				Total Break Cost		
Cmin	Cexp	Cmax	Cstoch7	CTmin	CTstoch	CTmax
4000	8000	24000	8520		32,390	
400	800	2400	857		17,885	
200	400	1200	429		17,051	

Costs in $1,000s

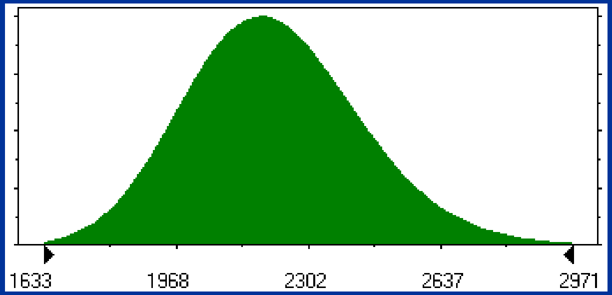
Typical Page From Hazard Spreadsheet

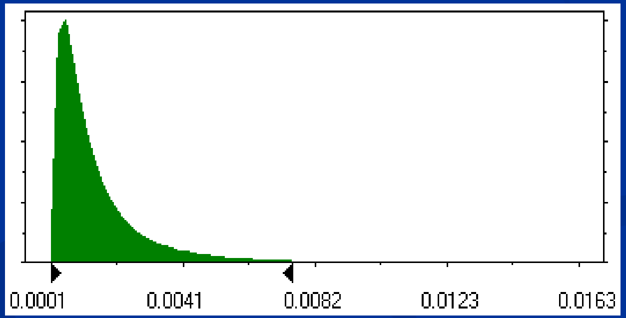
	Hazard 1 - Geotechnical											
	Leak Before Break Cost		Failure Probability				Leak Before Break Prob.				Failure Cost	Risk $ per Year
Name	Break Cost	CTstoch	fmin	fexp	fmax	fstoch1	Lmin	Lexp	Lmax	Lstoch		
A 1	1,000	32,390	0	0.0015	0.0075	0.0013	0	0.83	1	0.73	9,516	12
A 2	1,000	17,885	0	0.0015	0.0075	0.0013	0	0.83	1	0.73	3,870	5
A 3	1,000	17,051	0	0.0015	0.0075	0.0013	0	0.83	1	0.74	3,729	5

- Hazards Considered
  - Geotechnical
  - Hydrologic (flood, storms, etc.)
  - Seismic
  - Equipment Malfunction
  - Other Site Specific Hazards

Costs in $1,000s

Typical probability density functions for hazards and risks





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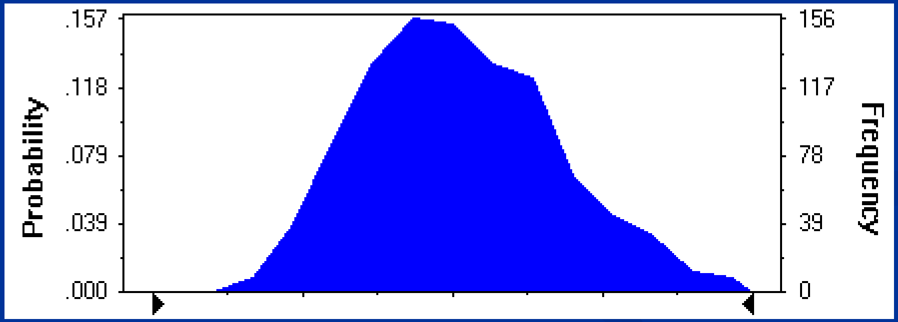


Top 10 List

Rank	Facility	Critical Hazard	Est. Failure Probability (ocurr/yr)	Est. Conseq Related to Crit Hazard (1000$/yr)	Risk (1000$/yr)	Comments
1	B	Geotechnical	0.0510	51,988	2,650	On-going monitoring program. Project is underway to stabilize slope of siphon.
2	C 2	Geotechnical	0.0486	50,935	2,473	On-going monitoring program. Analyses underway to determine extent of slope instability.
3	P 5	Geotechnical	0.0076	59,657	455	Monitoring program in place.
4	P 3	Equip Malfunction	0.0012	73,263	84	
5	C 1	Equip Malfunction	0.0012	67,677	83	Project underway to replace governors.
6	H	Equip Malfunction	0.0003	301,506	81	High risk is due to high consequences of failure. There is little that can be done to reduce risk. High risk emphasizes need for proper maintenance and careful operation.
7	H	Geotechnical	0.0015	53,611	79	High risk is due to high consequences of failure. There is little that can be done to reduce risk. High risk emphasizes need for proper maintenance and careful operation.
8	P 1	Equip Malfunction	0.0012	67,780	78	Project underway to improve equipment operation.
9	D 1	Equip Malfunction	0.0012	56,636	67	Needs testing and analysis.
10	K	Equip Malfunction	0.0012	42,359	50	Needs testing and analysis.

Benefits From Development of Penstock Risk Assessment Program

- Can use data from PMO type studies to evaluate penstocks
- Procedure can be used for other types of projects
- Procedure can be used to evaluate need for studies

Consequences of Penstock Failure

- Life Safety – Relatively low
- Economic – Can be relatively high

Findings

- Material degradation generally not a problem
- Older control systems often are unable to limit pressure rises
- Most failures of in-service penstocks were due to equipment malfunction or geotechnical failure

Things to Consider

- Appropriate inspection/testing
- Potential damage due to inspection
- Evaluation of inspection/testing

Why Inspect Water Conveyance Systems?

- Potential for loss of life
- Potential for environmental damage
- Potential for very large expenditure by licensee

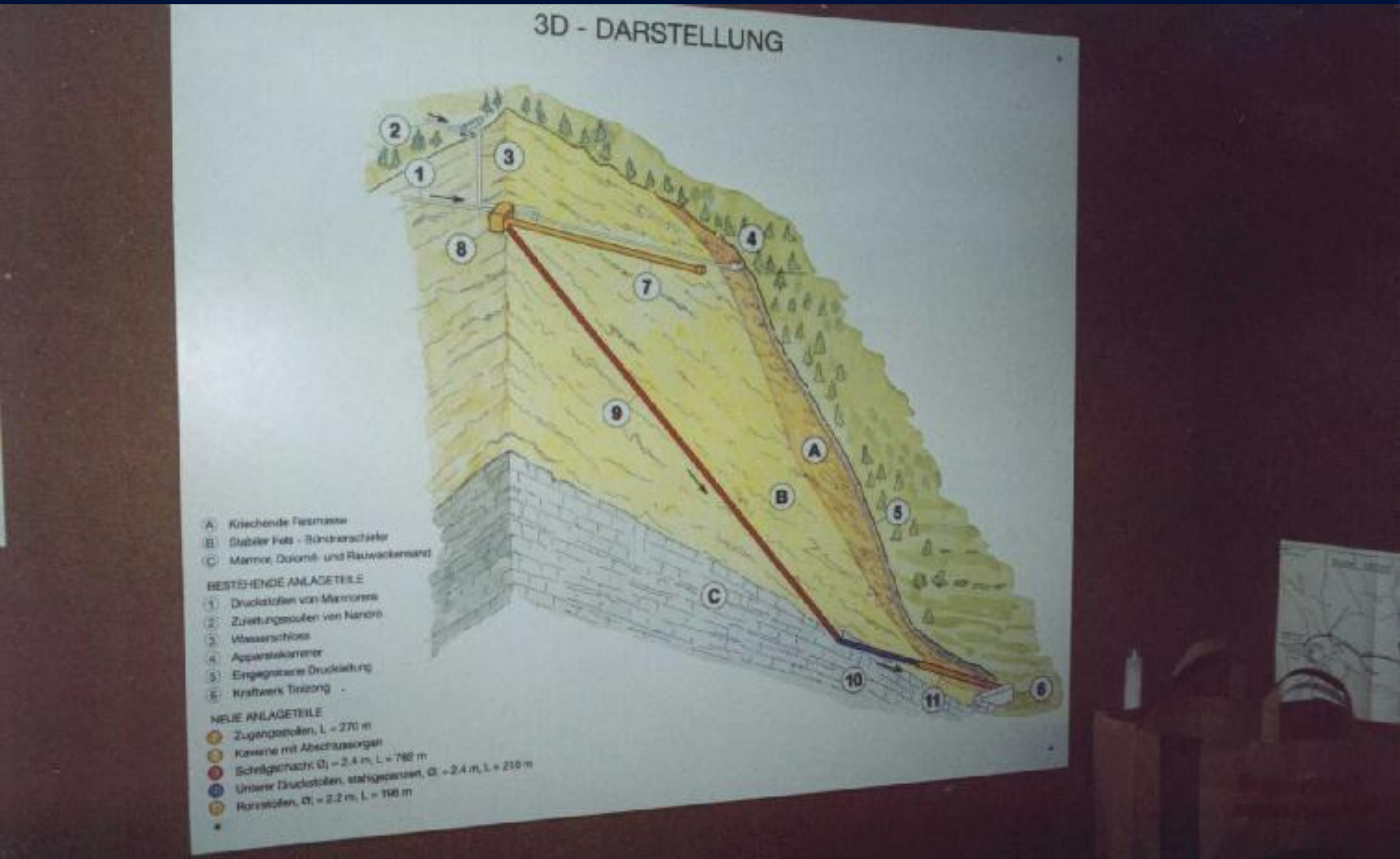
Key Inspection Items

- Geotechnical considerations
- Transient Pressures
- Material Problems

Issues

- Operation issues
- Access for inspections
- Inspection opportunities in current power market

Risk Reduction



3D - DARSTELLUNG
A Kriechende Felsmasse
B Stabiler Fels - Bündnerschiefer
C Marmor, Dolomit- und Rauwackenband
BESTEHENDE ANLAGETEILE
1 Druckstollen von Marmorera
2 Zuleitungsstollen von Nandro
3 Wasserschloss
4 Apparatekammer
5 Eingegrabene Druckleitung
6 Kraftwerk Tinizong
NEUE ANLAGETEILE
Zugangsstollen, L = 270 m
Kaverne mit Abschlussorgan
Schrägschacht, Øi = 2.4 m, L = 782 m
Unterer Druckstollen, stahlgepanzert, Øi = 2.4 m, L = 210 m
Rohrstollen, Øi = 2.2 m, L = 196 m

You Don’t Always Win


Caribou 1 Penstock
Caribou 2 Penstock
Caribou 1 PH
Caribou 2 PH

Thoughts

- Risk can help you make better, more informed decisions related to penstocks and other water conveyance facilities.
- You will need the best available information if you want good results

Garbage in, Garbage out

- Sharing our knowledge of penstock incidents will improve everyone's operational safety.